Parachute Inflation and Opening Shock

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Parachute Seminar

3rd International Planetary Probe Workshop

Outline

- Maximum parachute structural loads almost always occur during inflation
- Performance predictions frequently require accurate inflation time predictions

Why Study Parachute Inflation Theory ?

- **Maximum parachute structural loads almost always occur during inflation**
- **Performance predictions frequently require accurate inflation time predictions**
  - **Usually less important than loads**

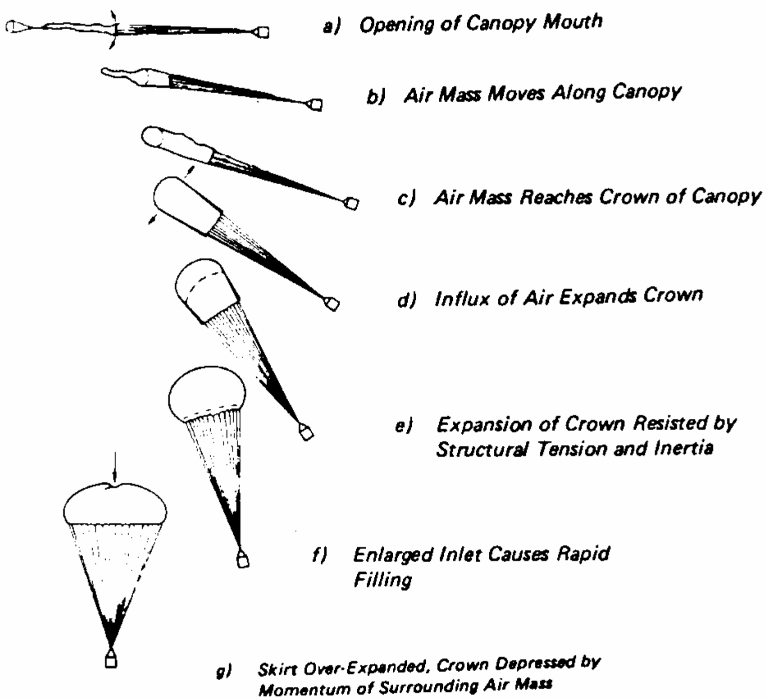
Is Parachute Inflation Theory a Difficult Topic ?

- **Fluid Mechanics**
  - **Unsteady, viscous often compressible flow about a porous body with large shape changes**
- **Structural Dynamics**
  - **A tension structure that undergoes large transient deformations**

Is Parachute Inflation Theory a Difficult Topic ?

- **Materials**
  - **Nonlinear materials with complex strain, strain rate and hysteresis properties**
- **Coupling**
  - **All of the above disciplines are strongly coupled**

Parachute Inflation Stages



- **Initial inflation until vent pressurized**
- **Final inflation fro vent pressurization to full open**
- **Initial inflation can start during deployment**
  - **Usually desirable**

Steady Flow Equation

- **Bernoulli equation for steady, inviscid, incompressible flow along a streamline (perfect fluid)**

$$\frac{P}{\rho} + \frac{1}{2} V^2 = C$$

  - **P = pressure**
  - **ρ = density**
  - **V = velocity**
  - **C = constant**

Steady Flow Around Sphere

- **Pressure distribution on a sphere in steady, inviscid, incompressible flow (perfect fluid)**

$$\frac{P - P_\infty}{\rho} = \left(\frac{9}{8}\cos^2\theta - \frac{5}{8}\right) V^2$$

  - **P_∞ = pressure far from sphere**
  - **θ = angle from stagnation point**

Steady Flow Drag Force

- **Drag force on body in steady flow**

$$D = C_d \frac{1}{2} \rho V^2 S$$

  - **D = drag**
  - **C_d = drag coefficient**
  - **S = area**

Perfect Fluid Steady Flow

- **Simple fluid model gives the correct functional form for drag force**
- **Shape of pressure distribution and magnitude of drag force are incorrectly predicted**
- **Real fluid effects due to viscosity and compressibility must be accounted for in pressure and drag coefficients**

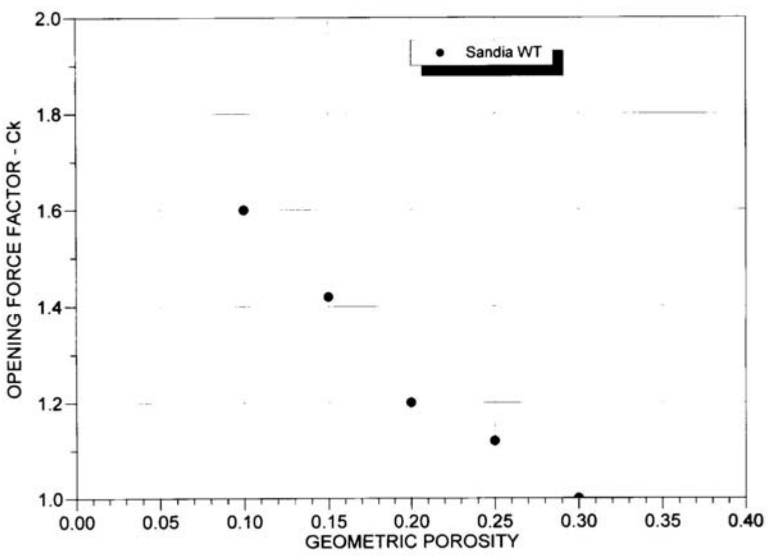
Parachute Opening Shock

- **The simplest form of estimating parachute opening shock load is to modify the steady drag equation**
  - $F_{max} = C_k C_d A Q$
  - C_k is parachute opening shock factor
  - C_d is parachute drag coefficient
  - A is reference area
  - Q is dynamic pressure

Parachute Opening Shock Factor

- **Infinite mass opening shock factor is primarily a function of canopy porosity**
  - **Infinite mass implies no deceleration during inflation**
  - **Maximum load occurs at maximum diameter**
- **Finite mass opening shock factor is primarily a function of mass ratio (characteristic fluid mass/system mass)**
  - **Finite mass implies significant deceleration during inflation**
  - **Acceleration of a large fluid mass (relative to system mass) causes system deceleration due to momentum transfer**
  - **Maximum load occurs early in inflation process**

Infinite Mass Opening Shock Factor

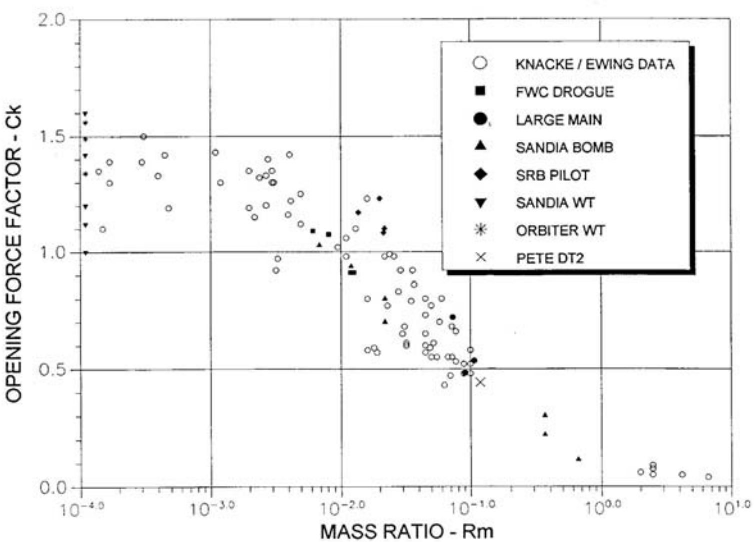


- **Wind tunnel data for models with only geometric porosity variations**
- **Disreefed from nearly closed to full open in steady flow**
- **High opening shock the result of faster inflation at low porosities**

Finite Mass Opening Shock Factor

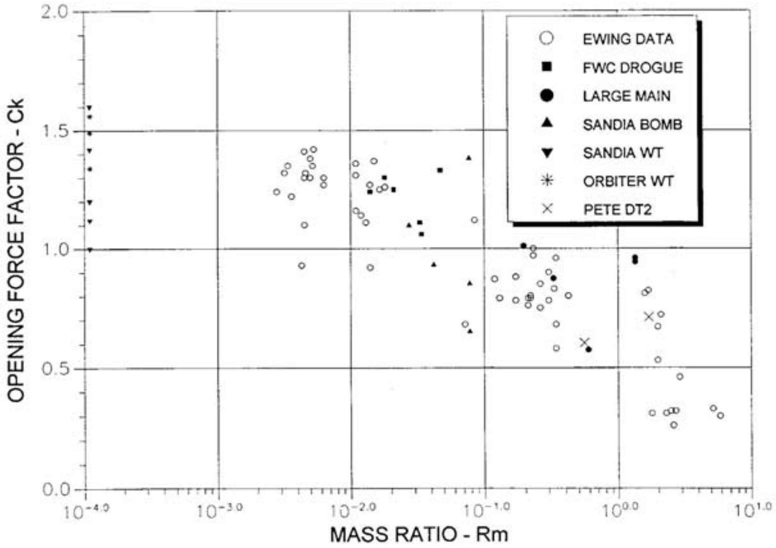
- **Finite mass opening shock factor is primarily a function of mass ratio (characteristic fluid mass/system mass)**
  - Inverse ratio (system mass/characteristic fluid mass) also sometimes used
- **Most common mass ratio used is $[\rho(C_dS)^{1.5}/M]$**
  - Where ρ is atmospheric density
  - C_dS is parachute drag area
  - M is system mass
- **Most extensive correlations**
  - Ewing AFFDL-TR-72-3
  - Knacke NWC TP 6575

Finite Mass Opening Shock Factor



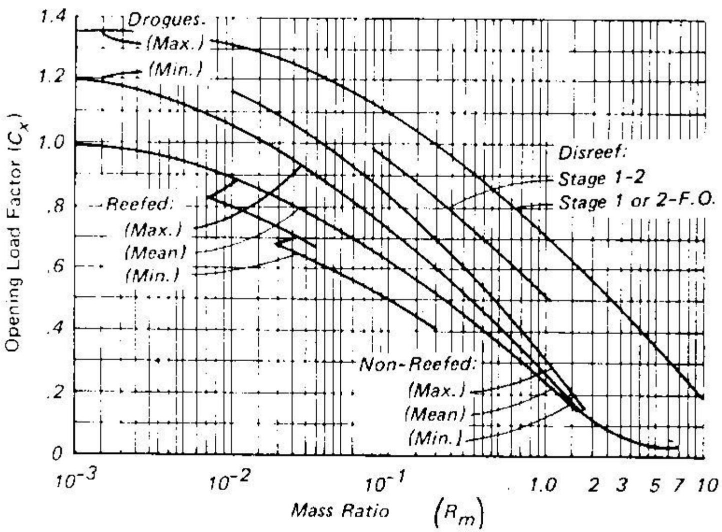
- For unreefed parachute or inflation to 1st reefed stage
- Data from other sources added to Knacke/Ewing data
- Data near Y-axis from infinite mass wind tunnel tests

Finite Mass Opening Shock Factor



- For disreef of reefed parachute
- Data from other sources added to Knacke/Ewing data
- Data near Y-axis from infinite mass wind tunnel tests

Finite Mass Opening Shock Factor



- Ewing/Bixby/Knacke AFFL-TR-78-151
- Same data set as Knacke/Ewing data
- More specific data correlations from subsets of the data
- Extremes of data scatter shown with mean values

Parachute Load Estimates

- **Finite mass opening shock factors can be used to provide rapid estimates of parachute opening loads**
  - **No computer code required**
  - **Calculator or “back of the envelope” estimate**
  - **Might need atmosphere table**
  - **Accurate enough for most parachute design work**
  - **Quick “sanity check” for computer codes**

Unsteady Flow Equation

- **Bernoulli equation for unsteady, inviscid, incompressible and irrotational flow along a streamline (perfect fluid)**

$$\frac{P}{\rho} + \frac{1}{2} V^2 + \frac{\partial \phi}{\partial t} = C(t)$$

  - **φ = velocity potential (grad φ = V)**
  - **t = time**

Unsteady Flow Around Sphere

- **Pressure distribution on a sphere in unsteady, inviscid, incompressible and irrotational flow along a streamline (perfect fluid)**

$$\frac{P - P_\infty}{\rho} = \left(\frac{9}{8}\cos^2\theta - \frac{5}{8}\right)V^2 + \frac{1}{2}R\cos\theta\,\frac{\partial V}{\partial t}$$

  - **R = radius of sphere**

Unsteady Flow Kinetic Energy

- **For the same unsteady flow (unsteady, inviscid, incompressible, irrotational), the fluid kinetic energy can be written**

$$T = \frac{1}{2} A_x V_x^2$$

  - **T = kinetic energy**
  - **A_x = a fluid mass**
  - **V_x = velocity of fluid mass (body)**

Unsteady Flow Force

- **The unsteady fluid force on a body in one-dimensional motion is**

$$F_x = -\frac{d}{dt}\left(\frac{\partial T}{\partial V_x}\right) = -A_x \frac{dV_x}{dt}$$

- **For a sphere, A_x can be written**

$$A_x = C_{ax} \frac{4}{3} \rho \pi R_p^3$$

C_{ax} = 0.5 (apparent mass coefficient)

R_p = parachute radius

Ballistic Equations of Motion

- **The equations of motion used in most simple trajectory computer codes are the ballistic or zero angle of attack equations**

$$(m + A_x)\frac{dV_x}{dt} = m\,g\sin\gamma \;-\; C_d\,\frac{1}{2}\rho\,V_x^2\,S$$

$$(m + A_x)V_x\,\frac{d\gamma}{dt} = m\,g\cos\gamma$$

m = system mass

g = gravitational acceleration

γ = trajectory angle

Dimensionless Equations

- **The ballistic equations can be written in dimensionless form**

$$\frac{dV_{x^*}}{dt^*} = \frac{\sin\gamma}{F_r\left(1+\frac{C_{ax}}{K_t}\right)} - \frac{\frac{3}{8}C_d V_x^2}{\left(K_t + C_{ax}\right)}$$

$$\frac{d\gamma}{dt^*} = \frac{K_t \cos\gamma}{F_r V_{x^*}\left(K_t + C_{ax}\right)}$$

Dimensionless Variables and Parameters

- **Dimensionless Variables**

$$V_{x^*} = \frac{V_x}{V_0} \quad ; \quad t^* = \frac{t\,V_0}{R_p}$$

- **Dimensionless Parameters**

$$F_r = \frac{V_0^2}{gR_p} \quad ; \quad K_t = \frac{m}{\frac{4}{3}\rho\pi\,R_p^3}$$

V_0 = initial velocity

Unsteady Flow Around Expanding Decelerating Sphere

- **Pressure distribution on an expanding, decelerating sphere in inviscid, incompressible and irrotational flow**

$$\frac{P - P_\infty}{\rho} = \left(\frac{9}{8}\cos^2\theta - \frac{5}{8}\right) V_x^2 + \frac{1}{2} R\cos\theta \, \frac{dV_x}{dt}$$

$$+ \frac{3}{2} V_r^2 + R\frac{dV_r}{dt} + \frac{3}{2}\cos\theta \, V_x \, V_r$$

$$V_r = \frac{dR}{dt}$$

Unsteady Forces on Inflating, Decelerating Parachute

- **Axial force along flight path**

$$F_{xu} = -\left(A_x \frac{dV_x}{dt} + V_x \frac{dA_x}{dt} \right)$$

- **Radial force**

$$F_{ru} = -\left(A_r \frac{dV_r}{dt} + V_r \frac{dA_r}{dt} \right)$$

- **No axial/radial coupling**

Dimensional Analysis and Unsteady Flow Conclusions

- **Dimensional analysis identifies dimensionless parameters that influence opening shock and inflation time**
  - Mass ratio $K_t = m / [(4/3)\ \rho\ \pi\ R_p^3]$
  - Froude number $F_r = V_0^2 / (g\ R_p)$

- **Simplified perfect fluid analysis provides insight into functional form of forces and pressure distributions**

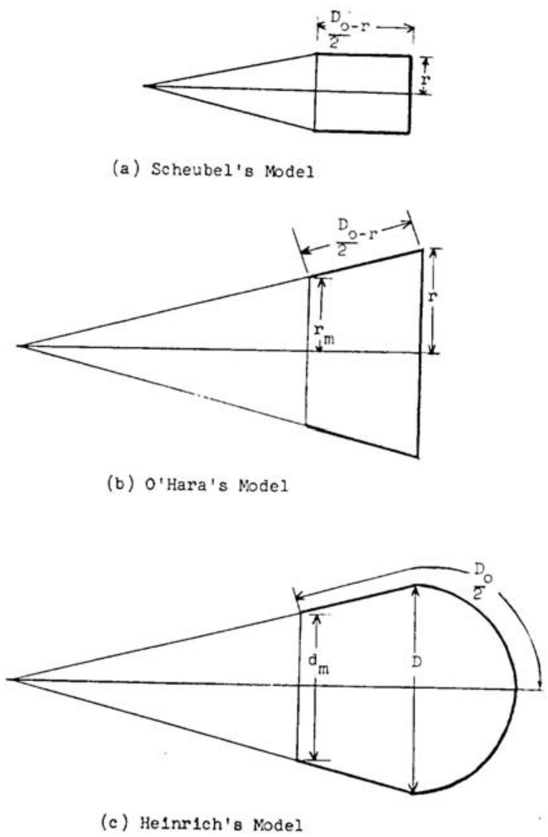
Drag Area vs Time Inflation Models

- **Simplest models specified drag area vs time as input to a point mass trajectory code**
  - **Inflation times often artificially adjusted to match loads**
  - **Inflation times sometimes scaled using dimensionless time**
- **Use of drag area as an independent variable in trajectory codes explains use of drag area directly to calculate mass ratio**
- **Combined use of point mass computer code and the mass ratio C_k correlations improved use of this method**

Continuity Equation Inflation Models

- More sophisticated models solved a conservation of mass equation for the parachute internal volume
  - Mass flow in determines rate of change of internal volume
  - Similar shapes used to get diameter and parachute drag
- Calculated shapes combined with point mass trajectory code
  - Apparent mass often used in equations of motion
- Extensive work by U. of Minnesota – Dr. Heinrich

Similar Shapes Used in Continuity Equation Inflation Models



- **Early shapes were simple because calculations were manual**
- **More realistic shapes allowed using computers**
- **Inflow and outflow assumptions required**

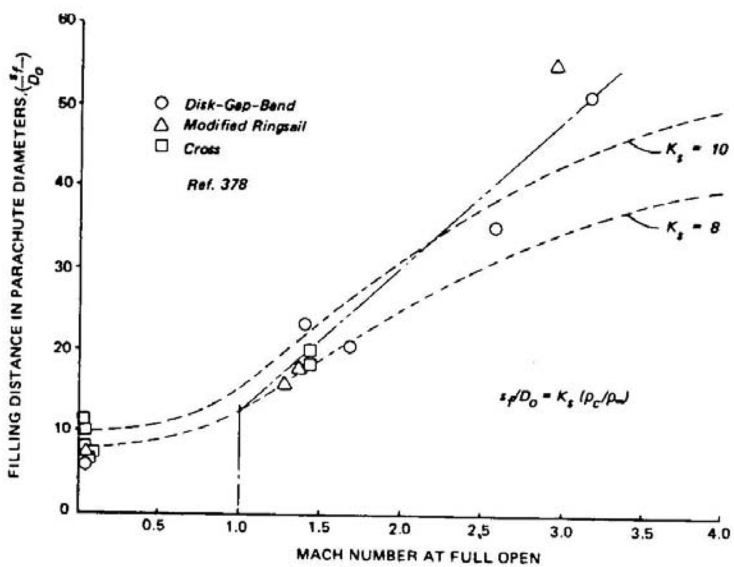
Constant Distance Theory Models

- Another family of inflation models was based on the observation that “a parachute always inflates in a fixed distance traveled”
- This assumption is equivalent to the conservation of mass assumption
  - A column of air ahead of the parachute eventually occupies the internal volume

Constant Distance Theory Models

- Both the conservation of mass and constant distance theory models assume dynamic similarity in the inflation process
  - Parachute mass ratio doesn't change much
- Instead of similar shapes, radial velocity can be directly specified to be a function of axial velocity
- A compressibility correction to constant distance theory was proposed

Proposed Compressibility Correction

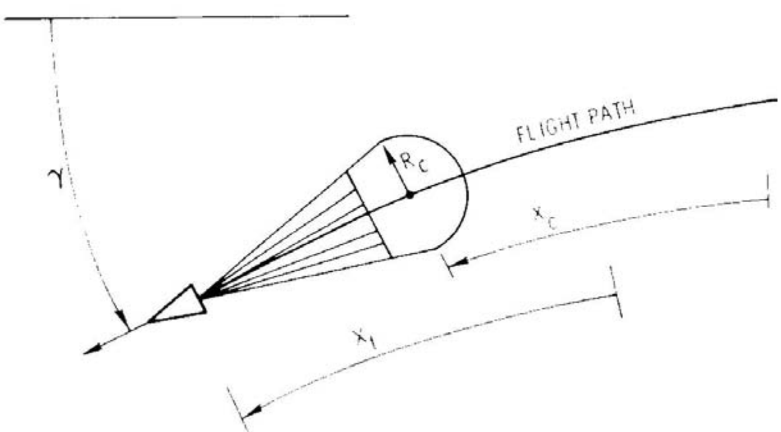


- Compressibility correction assumed normal shock ahead of canopy for density correction
- Wind tunnel photo and drag data show this is incorrect
  - Actual density change is small fraction of normal shock correction

Simple Dynamic Inflation Model

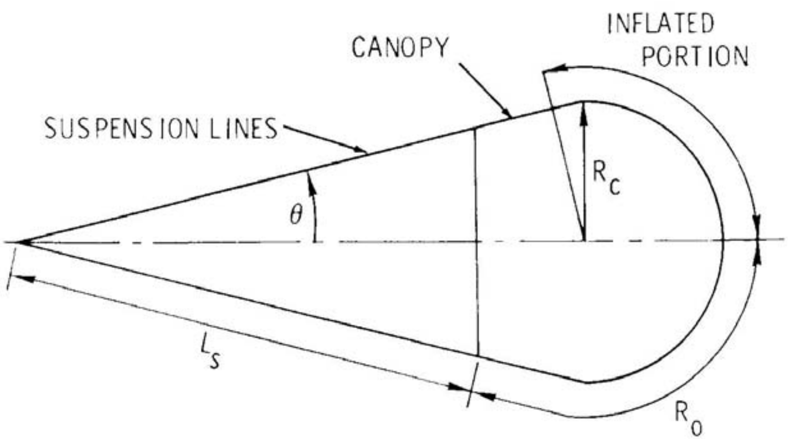
- **Model based on conservation of momentum**
  - Parachute inflation is a dynamics problem, not a quasi-static problem
  - Single radial degree of freedom
  - Rigid coupling parachute and payload
  - Unreefed parachutes only
  - Steady and unsteady aerodynamic effects

Trajectory for Model



- **Ballistic (zero angle of attack) trajectory**
- **Velocity at payload and parachute different because parachute moves toward payload during inflation**

Parachute Geometry for Model



- Similar shapes
  - Hemispherical inflated part
  - Conical uninflated part
- Rigid coupling between parachute and payload

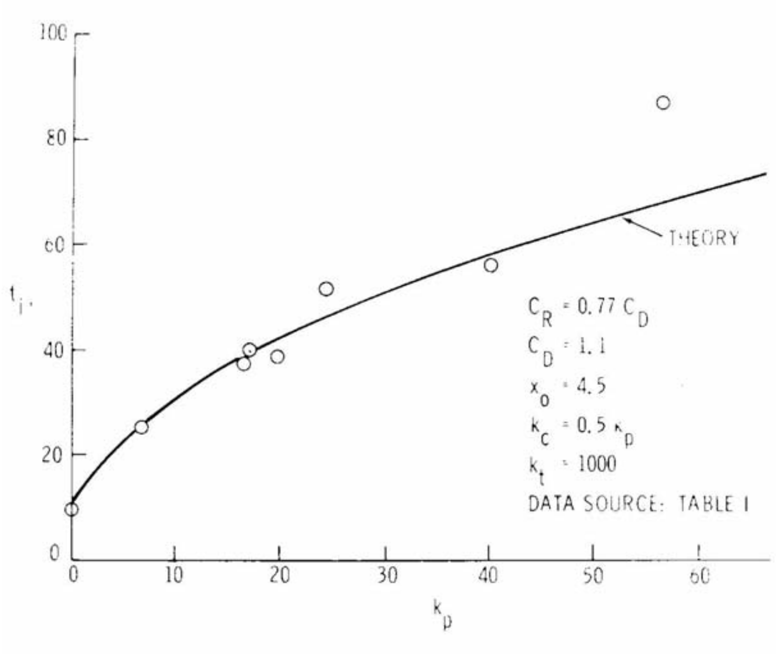
Simple Dynamic Inflation Model

- **Single canopy mass element located at maximum diameter point**
- **Steady radial force coefficient data based on inflated geometry**
- **Radial force to drag force ratio required to produce canopy shape was obtained from photographic data**

Simple Dynamic Inflation Model

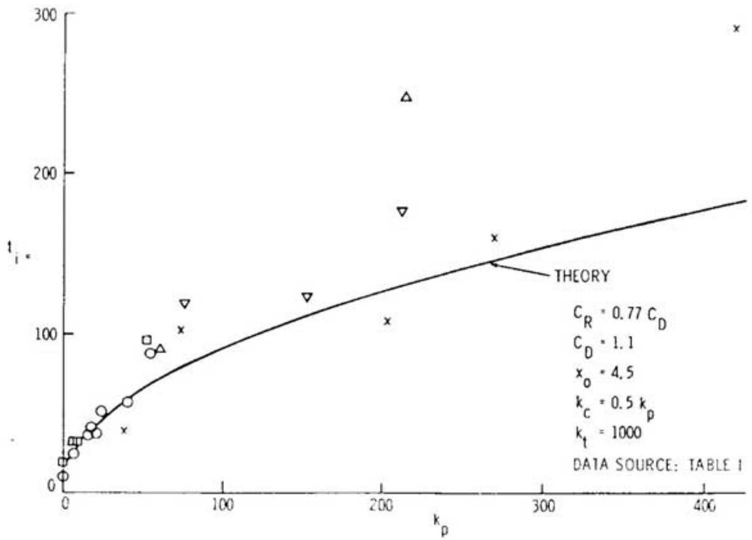
- Equations were put in non-dimensional form
  - A second mass ratio, the parachute mass ratio, was revealed
- Predictions of the model were compared with test data from the PEPP tests
- Predicted inflation time variations over the wide altitude range of tests agreed very well with PEPP data

Non-dimentional Inflation Times for DGB Parachutes



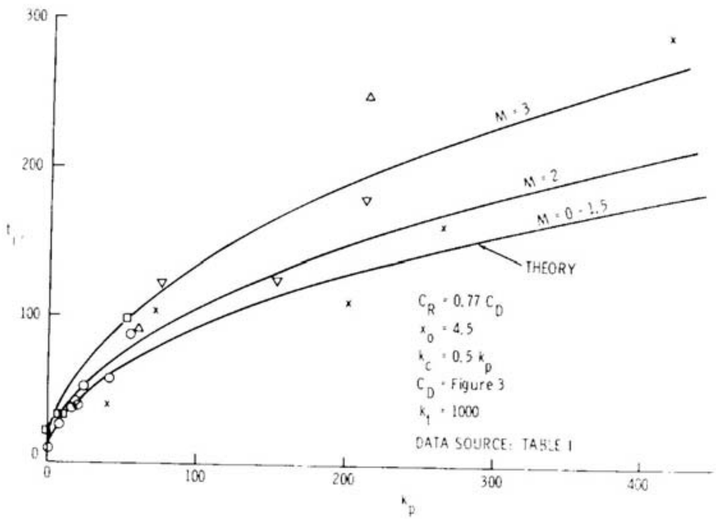
- **Dimensionless inflation times correlated well with parachute mass ratio over wide altitude range**
- **No compressibility correction**

Non-dimentional Inflation Times for all PEPP Parachutes



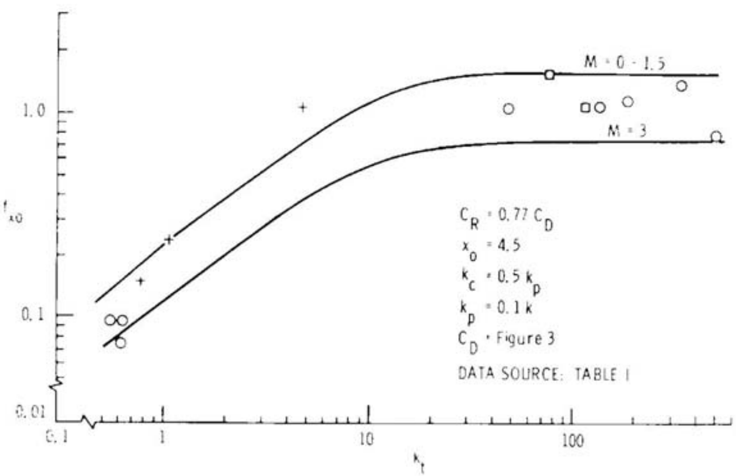
- Dimensionless inflation times correlated well with lower bound of data
- No compressibility correction

Non-dimentional Inflation Times for all PEPP Parachutes



- **Dimensionless inflation times with compressibility corrections based on density estimate required for drag coefficient vs Mach number variation**

Opening Shock Factor for all PEPP Parachutes



- Drag coefficient vs Mach number from wind tunnel data
- Predictions span range of data scatter

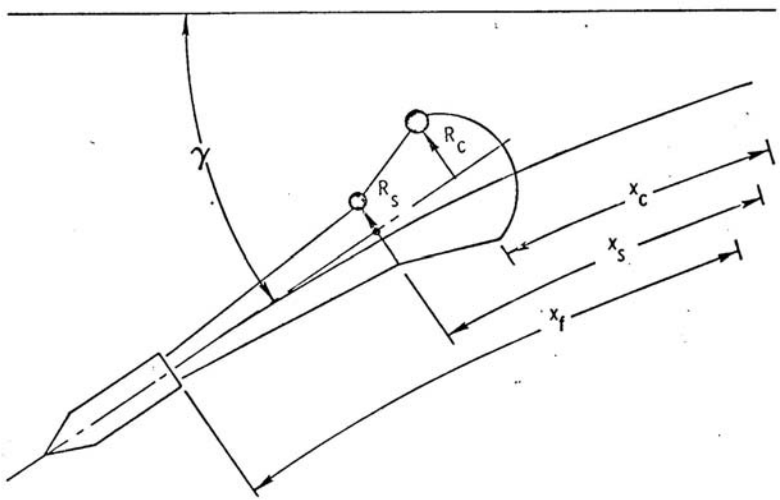
Conclusions from Simple Dynamic Inflation Model Study

- Parachute mass ratio should be considered an important scaling factor for use of parachutes in low density environment
- Compressibility correction appears to be much less than proposed for constant distance theory models

More General Dynamic Inflation Model

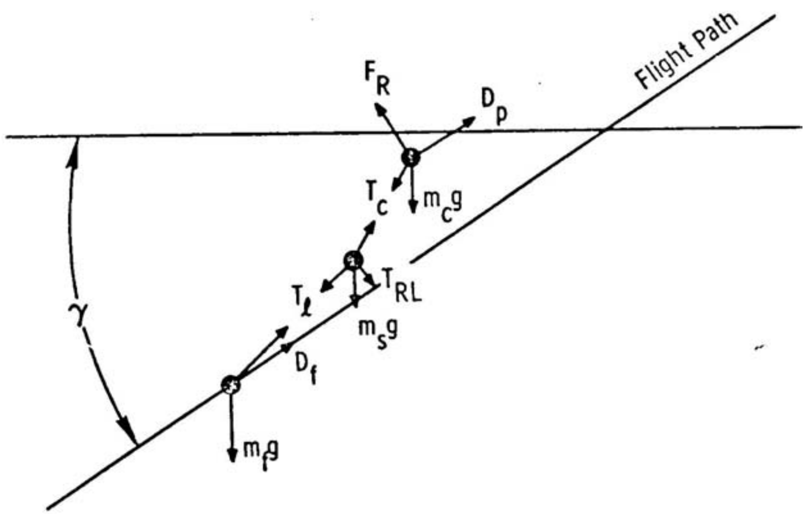
- Two radial degrees of freedom
- Elastic elements couple parachute masses and payload
- Can be used to model reefed parachutes
- Parametric aerodynamic data for different porosities measured to provide design data base

Trajectory for Model



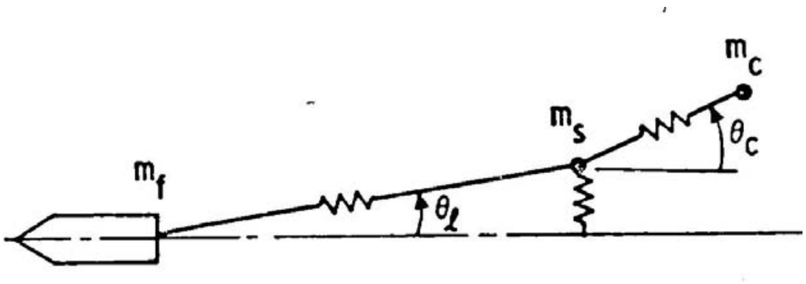
- **Ballistic (zero angle of attack) trajectory**
- **Velocity at payload and parachute different because parachute moves toward payload during inflation**

Forces on Mass Elements



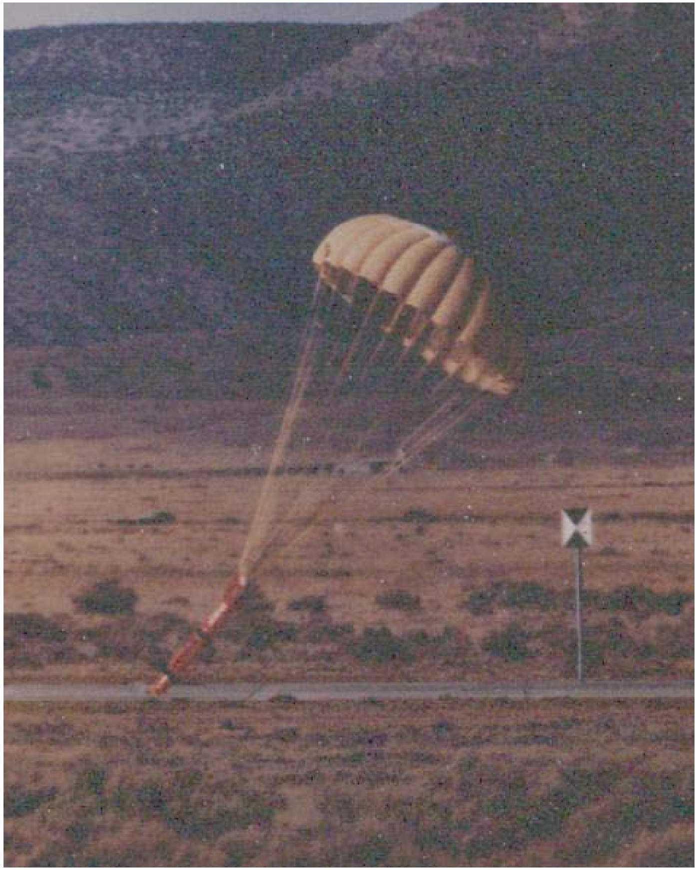
- **Two parachute mass elements**
  - **Maximum diameter**
  - **Skirt**
- **Radial force applied at maximum diameter element**

Elastic Constraints on Mass Elements



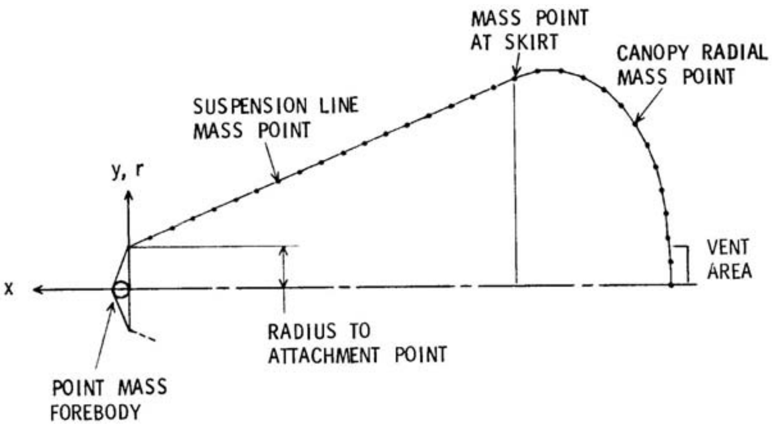
- **Allows different elastic properties for suspension lines and radials**
- **Realistic modeling of reefing line constraint and cutting of reefing line**

Use of Dynamic Inflation Model



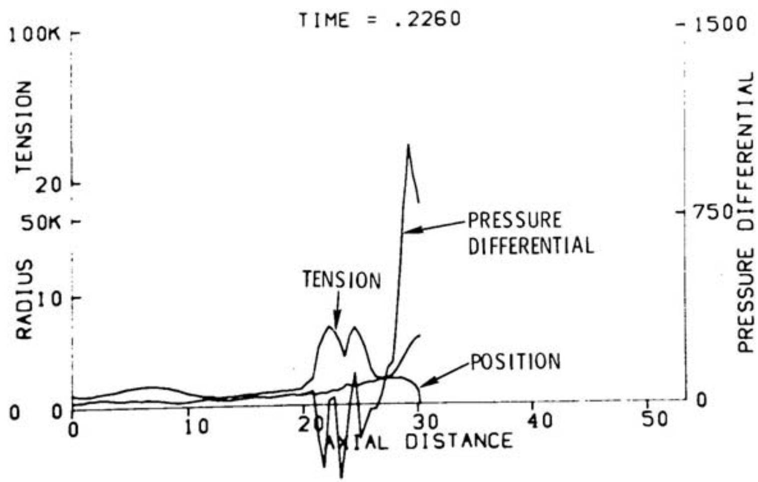
- Used to design many parachutes at Sandia
- Reefing easy to include
- Also used to study wake overtake which occurs during rapid deceleration

Multi-Element Dynamic Inflation Model

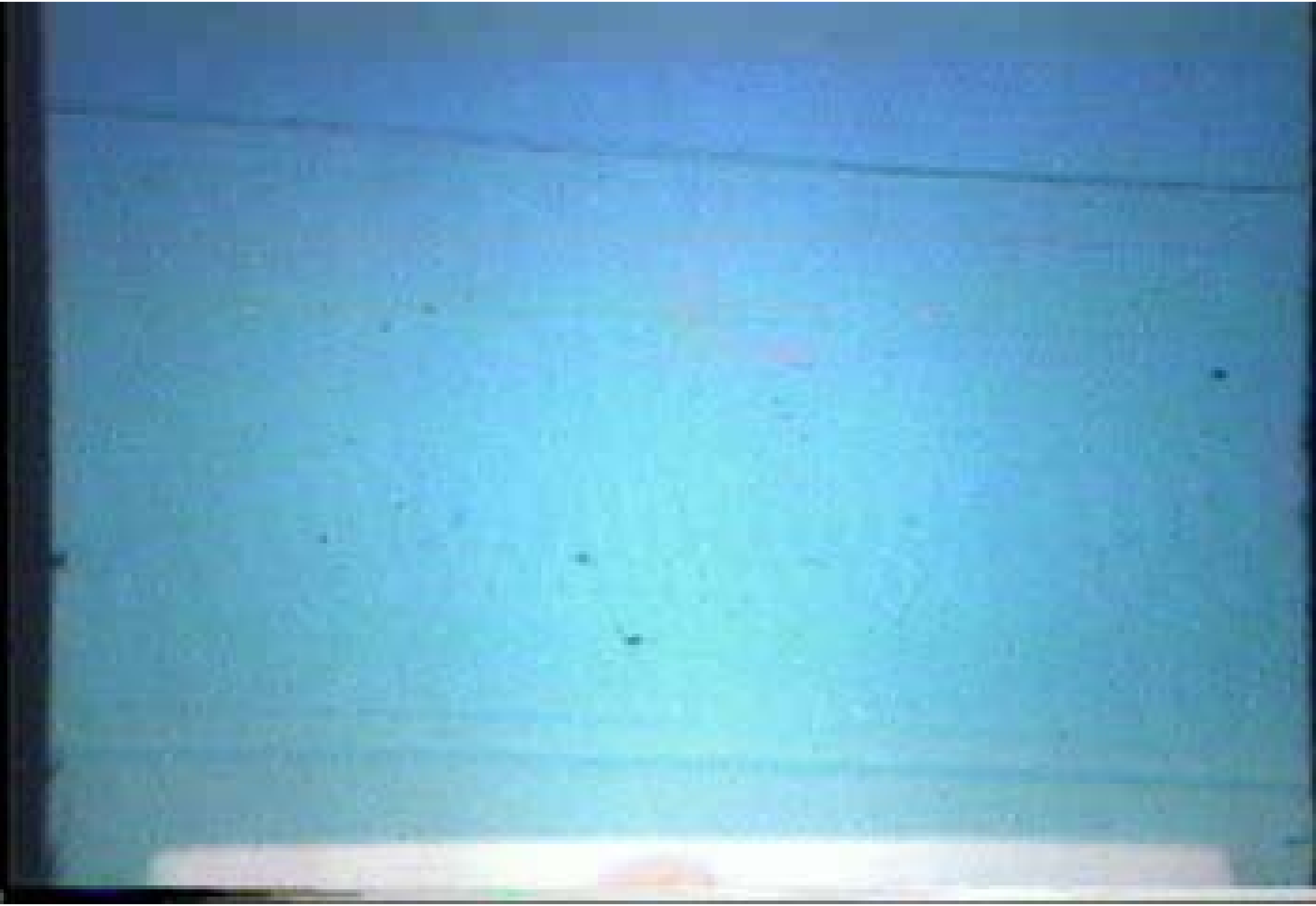


- **Many mass elements used to model parachute**
- **Used to study parachute deployment and inflation in greater detail**

Multi-Element Dynamic Inflation Model



- **Used to study variations of tension, radius, pressure and other variables along length of parachute**




DEPLOYMENT CONDITIONS
VELOCITY = 1025 FPS
DYNAMIC PRESSURE = 1100PSF